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Military Applications of Microelectromechanical Systems

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National Defense Research Institute
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Prepared for the
Office of the Secretary of Defense
United States Air Force
United States Army

National Defense Research Institute
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Preface

This report presents results from an exploratory effort that examined potential military applications for microelectromechanical systems (MEMS). The project examined the potential military utility of microsystem technology, particularly as applied to a small number of posited military applications. The example applications ranged from the relatively simple and near term to the extraordinarily challenging.

The project also collected views from researchers in the MEMS community on what form of government program would further the field in the near term. Recommendations are presented regarding a U.S. military program in microsystem research and development.

The main body of research represented here was concluded in December 1991. An early draft was distributed at a workshop on "Technology-Driven Revolutions in Military Operations," sponsored by the Defense Advanced Research Projects Agency and held at RAND in December 1992.

The preparation of this report was supported by RAND's Defense Planning and Analysis Department, using funds from the concept-formulation and research-support component of RAND's federally funded research and development centers (FFRDCs) for national security studies. Those centers are Project AIR FORCE, sponsored by the United States Air Force; the Arroyo Center, sponsored by the United States Army; and the National Defense Research Institute, sponsored by the Office of the Secretary of Defense and the Joint Staff.

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Summary

Microelectromechanical systems (MEMS) or, more broadly, microengineered systems are essentially small devices on the scale of a few millimeters or less. They are often made using variations on techniques used in fabricating electronics; silicon is etched to create very fine, often very flat, structures. However, instead of transistors and diodes, small motors, gears, and sensors are made. Other techniques such as deep X-ray (synchrotron) lithography, electric discharge machining, and acoustic laser etching are also employed, often to create three-dimensional structures. These and other techniques are touched upon in the body of this report.

A number of fascinating microengineered devices have been developed, many at sizes almost invisible to the naked eye. These inventions include rotary motors, linear actuators, accelerometers, resonators, gears, levers, cams, rods, tools such as pincers, and any number of other components. To date, transducers have demonstrated the most promising commercial applications: accelerometers, inertial guidance systems, chemical sensors, and the like. In fact, one of the major conferences at which microengineering research is presented is the *Transducers* series—conferences concentrating on sensor components.

The MEMS field is evolving at a rapid pace. Several nations, such as Japan and The Netherlands, have identified MEMS as one of the more important areas of research for the next decade. The topic has received a large measure of attention in the press; scientific conferences such as the MEMS series dating from 1988 have become well attended, and a number of journals are either now dedicated to the issue or feature it frequently. Although a number of Department of Defense officials, most notably at the Defense Advanced Research Projects Agency (DARPA), have addressed microsystem engineering, little has been published on the potential MEMS may have for advancing military technology, the topic here.

MEMS hold forth several attributes that make the technology attractive for systems developments. Complete systems on the scale of a few millimeters or less may be mass produced at low cost. The systems may be designed to be rugged and self-diagnostic. Mechanical actuation and three-dimensional structures at the micron-level open design possibilities that were unthinkable only a few years ago.

Countervailing the promise of MEMS lie enormous challenges in developing the technology. The MEMS field is still in its infancy. Strides have been made, but one cannot point to a truly breakthrough system or component that cements MEMS as a cornerstone technology along the lines of, say, microelectronics. Therefore, in this study, we concentrate on examining potential MEMS systems that might offer significant capabilities to meet outstanding military needs.

We adopted a case method approach. We posited a few specific military applications and then discussed them with a number of U.S. researchers in the MEMS field. Most researchers with whom we spoke, with a few notable exceptions, had given little thought and even less research effort to the subject of military systems. We talked to a number of government officials who had given the subject ample consideration, but again, little has been done at the systems level.[1]

We sketch five potential military applications in this report. They are all system applications, that is, MEMS technology provides the key equipment for a military system.[2] We make no claim that these are the best applications or approaches. They simply give us a concrete form with which to understand what sorts of technologies would appear useful to a system designer. The five systems are:

- Chemical sensor for the soldier
- Identification friend or foe
- Active surfaces
- Distributed sensor net
- Microrobotic electronic disabling system

The first application, a chemical sensor for the soldier, would give individual soldiers accurate and timely information regarding noxious battlefield chemicals. The identification friend or foe device is based on minute corner reflectors and would enable soldiers to more easily distinguish their own forces from enemy forces. Active surfaces refer to the types of applications that may become feasible once minute sensors and actuators can be proliferated throughout a material. The distributed sensor net concept envisions a MEMS approach that renders future battlefields more transparent. The microrobotic electronics disabling system is a concept that addresses the potential weaponization of MEMS.

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[1] This statement was true at the time we conducted the bulk of our interviews (December 1991).
[2] We specifically did not consider applications for intelligence gathering.

These systems are listed, to our best knowledge, from least to most difficult to attain. The applications were chosen for their military worth, their technical variety, and their produceability. Each represents a concept that utilizes the unique properties of MEMS technology; that is, the specific system could not have been achieved without resorting to MEMS. Although the field is too young for us to predict if or when any of these posited applications may become feasible, not a single researcher with whom we discussed these systems thought them impossible. Also, some simple first-order calculations were made to check for basic physics limitations, and none were found.

There remain the issues of utility and comparative advantage—whether the systems posited here offer the user a truly needed capability and whether they are better than other approaches to meet the same ends. We do not rigorously address these issues in this report. We simply claim that, from our knowledge of military systems, the posited systems, if achievable, would appear to offer unique approaches to long-standing military problems.

Although it may be problematic to prove the military utility of MEMS systems, it appears evident, given current trends, that the United States will soon no longer be the leader within the field. Indeed, a number of researchers believe that the United States has already relinquished its lead. Planned U.S. investments lag by an order of magnitude behind the first-tier MEMS investors of Japan, Germany, and The Netherlands. Since it is likely that MEMS technology will be developed more rapidly overseas, we recommend that the United States develop expertise in military applications of MEMS technologies both to capitalize upon breakthroughs if they occur and to develop countermeasures if they become necessary. The United States should, as a minimum, monitor the field closely with an eye toward the types of technological advancements that could be translated into militarily important systems.

As an activist measure, we would further recommend that the Office of the Secretary of Defense and the military branches develop and pursue reasonable target applications of MEMS technology for demonstration in the three- to five-year time frame. Such efforts would allow the military to truly assess the military potential of the technology. Even if some of the efforts fail, as would be expected from their high-risk nature, a modest activity of this kind would allow the military to capitalize on unforeseen breakthroughs that may come from military, civilian, or foreign research.

Acknowledgments

We would like to thank Dr. Calvin Shipbaugh for his constructive review. Dr. Paul Davis, Professor Stephen Jacobsen, Mr. Bruno Augenstein, and Dr. Lloyd Mundie also contributed in modifying our early drafts, for which we are grateful. Mr. Robert Zwirn developed concepts, performed calculations, and wrote Appendix A. Finally, we would also like to thank the many researchers in the MEMS community who took time from their busy schedules for our interviews and to comment on the report. Although the views represented in the report are ours, they surely benefited from all the help extended to us.

1. Introduction

Microelectromechanical systems (MEMS) received extensive coverage in the popular press beginning in the early 1990s.[1] Articles featured any number of eye-catching devices: gears no larger than a speck of dust, motors visible only through a microscope, actuators capable of sensing the presence of individual atoms. Perhaps someday surgeons will remotely pilot minute submarines to clear tumors and the planets will be explored cheaply and safely by thimble-sized spacecraft, but these applications are not the topic of this report.

Throughout modern history, technological advancement has brought military advancement in its wake. The industrial revolution gave us massive numbers of affordable firearms, iron-clad battleships, machine guns, and battle tanks. The invention of aircraft engendered entire military branches being created in most of the world's armies. The nuclear age brought a capability to wage a war quite unlike any other. One lesson that may be gleaned from this is that technological superiority often translates into military advantage.

Many scientists, engineers, and officials in a number of countries believe that MEMS will be one of the most fruitful technological endeavors of the next century, that MEMS could revolutionize any number of fields.[2] If their beliefs hold, historical analogy would indicate that MEMS could become a key military technology.

What could MEMS do for the military? What sorts of applications may become feasible? What risk would these systems pose to U.S. national security, and what countermeasures could the United States pursue? Does MEMS hold any promise for a truly fundamental breakthrough in how wars of the future may be fought? What type of MEMS program should the government pursue in the development of military applications for MEMS technologies? These are the questions we address. Since MEMS is such a new field, we cannot resolve our queries, but we

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[1] Among the many examples are: Gary Stix, "Micron Machinations," *Scientific American*, November 1992, pp. 106–117; Leslie Helms, "Big Hopes for Tiny Machines," *Los Angeles Times*, January 6, 1991, p. 1; William J. Broad, "Rotors and Gears for Tiny Robots," *New York Times*, January 1, 1991, p. 35; "Japan Pours Big Bucks into Very Little Machines," *Business Week*, August 27, 1990, p. 83; the 29 November 1991 issue of *Science* featured a number of nano and microengineering articles.

[2] *Small Machines, Large Opportunities: A Report on the Emerging Field of Microdynamics*, NSF Workshop on MEMS Research, 1988.

hope to at least sensitize the military community to potential changes that MEMS technology may allow.[3]

The remainder of this report is divided into four sections and two appendices. Section 2 introduces the reader to MEMS technology. Section 3 explores a number of posited military applications that would appear to either require or benefit greatly from MEMS technology. In Section 4, we present opinions of researchers within the U.S. MEMS community regarding the best direction for a MEMS program, and we give our own views and recommendations on the subject. In the final section, Section 5, we make a few overall observations.

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[3]Others, particularly the Defense Advanced Research Projects Agency (DARPA), have explored military applications of MEMS. DARPA has an active MEMS program and has generated several lists of potential applications.

2. Introduction to MEMS Technology

In this section, we present a brief overview of MEMS technology to enable readers unfamiliar with the field to better understand our arguments and observations regarding military applications of the technology.

This section is divided into three subsections. In the first subsection, we examine how MEMS research is organized in the United States and abroad. Next, we summarize the various fabrication techniques used by the MEMS community. Last, we look at some current applications for MEMS and applications anticipated by those in the field.

International Organization of MEMS Technology

The United States is the generally acknowledged leader in MEMS technology today, although a few researchers would accord that title to Japan. However, few observers expect the United States to maintain this lead for more than a year or two given the extraordinary investments being undertaken throughout the international community. International investments may be organized into three tiers: primary investors, secondary investors, and tertiary investors. The United States falls within the secondary tier, as shown in Table 1.

The largest investor in MEMS research is projected to be Japan. Japan's Ministry of International Trade and Industry (MITI) has laid out a 10-year program of MEMS research in which industry is expected to participate heavily. Of the $150

Table 1

Projected 1992 International MEMS Research Expenditures

Country	Research ($M/yr)
Japan	150–200
The Netherlands	100
Germany	70–100
United States	15–20
Switzerland	5–10
Canada	4–5

NOTE: Figures are rough estimates gathered from reports of government expenditures and from surveying U.S. researchers and government officials (December 1991).

million to $200 million per year projected, two-thirds of those funds would come from industry. The Japanese investment is all the more striking in that these monies are generally recognized as new, not merely renamed continuing programs. Toyota in particular is said to have an impressive MEMS research and manufacturing capability. Although the Japanese are generally viewed as currently being behind the United States in MEMS technology, one may note that the most advanced manufacturing equipment required for MEMS development is either Japanese or German in origin.

We found The Netherlands to hold a rather surprising position among the first-tier countries, where Delft University has taken the lead. We were told by U.S. officials following MEMS technologies that The Netherlands has identified MEMS as one of the key technology areas in which it wishes to build a future capability.

The estimated German expenditure may be somewhat misleading since a portion of the $70+ million figure comes from renaming its X-ray lithography work as MEMS-related activities. However, even with the redesignation, the planned German investment remains sizable.

Projected U.S. expenditures fall roughly an order of magnitude below those of first-tier countries. The United States has enjoyed a period in which it has led the field since its inception in the mid-1980s. However, given the widely disparate levels of investment between the United States and the first-tier countries, it is difficult to see how this lead can be maintained.

While U.S. industry contributes substantial efforts in sensor-related fields such as pressure transducers, displacement transducers, strain gauges, and accelerometers, almost all of the research on mechanical systems is conducted by universities. A list of major U.S. facilities involved in MEMS activities, especially actuators, along with principal investigators and areas of concentration is shown in Table 2.[1] One may note that Bell Laboratories, the sole industrial participant on this list, has recently withdrawn from the MEMS field altogether.

The wide diversity of activities may be more of a measure of the immaturity of the field than any particular robustness on the part of U.S. research. In fact, most of the activities are funded with relatively small research grants. For example, BSAC (Berkeley Sensor and Actuator Center) and the Utah CED (Center for Engineering Design), two of the largest MEMS R&D organizations in the United

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[1]Not included in the list are small companies such as Sarcos, Novasensor, and IC Sensors. A number of corporations involved primarily in transducer developments are shown in Table 3.

Table 2

U.S. Organizations Involved in MEMS Research[a]

Organization	Principal Investigators	Areas of Activity
Berkeley Sensor and Actuator Center	Richard Howe[b] Richard Muller Albert Pisano Richard White	Biologic interfaces, piezoelectric pumps, piezoelectric microphones, pressure gauges, resonant microstructures
Massachusetts Institute of Technology	Rodney Brooks Dan Ehrlich Anita Flynn Jeffrey Lang Stephen Senturia[b]	Electrostatic and piezoelectric motors, laser silicon etching, MEMS computer-aided design (CAD), robotics
University of Utah	Steve Jacobsen John Wood	Active surfaces, electrostatic motors, magnetic wobble motors, robotics/prosthetics, mechanical microsensors
University of Michigan	Selden Crary Khalil Najafi Johannes Scwank Ken Wise	Chemical sensing, load measurement, MEMS CAD, neural probes, silicon processing
University of Wisconsin	Henry Guckel	LIGA (lithography, galvanoformung, abformung) processing, magnetic micromotors, microresonators, pressure transducers
Bell Laboratories (withdrawn from the field)	Ken Gabriel William Trimmer (Neither currently with Bell)	Electrostatic motors, integrated circuit (IC)-based manufacturing, silicon processing, shape memory alloy (SMA), and piezoactuators
Carnegie-Mellon University (CMU)	Pradeep Khosla Michael Reed Edward Schlesinger	Medical pumps/flow meters/structures, optical actuators, robotics
Case Western University	M. Mehreghani[b]	Electrostatic motors, material microstructure, microrobotics
Louisiana Technology University, Louisiana State University	Robert Warrington	LIGA, diamond bit micromachining, photolithography and chemical etching
New Jersey Institute of Technology	William Carr Robert Marcus[b]	Micromachined vacuum devices, microstructures, magnetic sensors
Cornell	Noel McDonald	National nanofabrication facility

NOTE: We also discussed MEMS technologies and applications with a number of government representatives, such as: S. Hazlrigg (National Science Foundation), LTC J. Beno (DARPA), and Dr. L. Glasser (DARPA).

[a]List is not comprehensive.

[b]Did not interview.

States, operate on budgets of $2 million to $4 million per year, only a portion of which is dedicated to MEMS.

MEMS Fabrication Techniques

In many ways, the methods used in fabricating MEMS devices are among the most divisive issues currently facing the MEMS community. The reason for this is that fabrication methods not only dictate how a given device may be built, but also whether that device may be built at all. Each fabrication method requires unique and expensive equipment, making it imperative to allocate resources effectively. Briefly, the issue is whether to invest in silicon-based methods for fabrication or to pursue other approaches. The advantage of using the traditional silicon-based fabrication methods of screening, etching, and depositing is that such methods would almost certainly lend themselves to mass production. However, these methods are much more limited than many designers would like, especially with respect to production of three-dimensional structures and the packaging of systems.[2] Other methods include the LIGA process, acoustic laser etching, nonplanar electron-beam lithography, sputtering, direct silicon bonding, electric-discharge machining, diamond micromachining, and even watchmaker skills. Several of these fabrication techniques will be discussed in more detail in the remainder of this section.

We concentrate on four areas of fabrication:

- Sacrificial layer silicon processing
- Bulk micromachining
- LIGA X-ray lithography
- Other processes

Within each of these areas, we broadly compare benefits and drawbacks of each technique. However, the reader should keep in mind that these are areas of intense debate within the MEMS community, and that the purpose of this section is simply to point out areas of difference, not to resolve those differences.

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[2]R. T. Howe et al., "Silicon Micromechanics: Sensors and Actuators on a Chip," *IEEE Spectrum*, July 1990, pp. 29–35.

Sacrificial Layer Silicon Processing

One of the earliest methodologies for fabricating MEMS devices was the sacrificial layer technique. Bell Labs and the Berkeley Sensor and Actuation Center independently pioneered this technique.[3]

Silicon processing is quite unlike normal macro-scale fabrication techniques. In the macro world, pieces are machined or cast individually and then assembled to create a final product. With the sacrificial layer technique, whole slabs of material are laid upon one another, and then selected portions of those slabs are etched away. The remaining structure is then the "preassembled device," whatever it may be.[4]

This technique is especially good for creating thin devices, normally 4 to 10 microns, from silicon and doped silicon materials. It has the great advantage of using wafer manufacturing techniques developed for the electronics industry. Therefore, MEMS devices developed via silicon processing hold forth the promise of being very inexpensive. They also tend to be more compatible with integrated electronics.

The technique has been applied extensively to developing electrostatic motors, silicon gears, and diaphragms for sensors. Three types of electrostatic motors are generally possible: rotary motors, wobble motors, and comb drives.[5] However, it should be stressed that these motors may be fabricated using any number of other techniques, as discussed later in this section.

A rotary micromotor is essentially a wheel in a wheel well. The rims of the wheel and wheel well each form a circuit of capacitors, as shown in Figure 1.[6] The capacitors are charged and discharged in a timed sequence that pulls the rim of the wheel along and causes it to rotate, forming a motor.

The wobble motor works on a similar principle, but with one distinctive difference. Unlike a rotary motor, in which the axle of the wheel maintains the rim at a specified distance from the surrounding stator, the central hub of the wobble motor is allowed to move, letting the rotor and stator make contact. Developed independently at the University of Utah and Bell Labs,[7] the wobble

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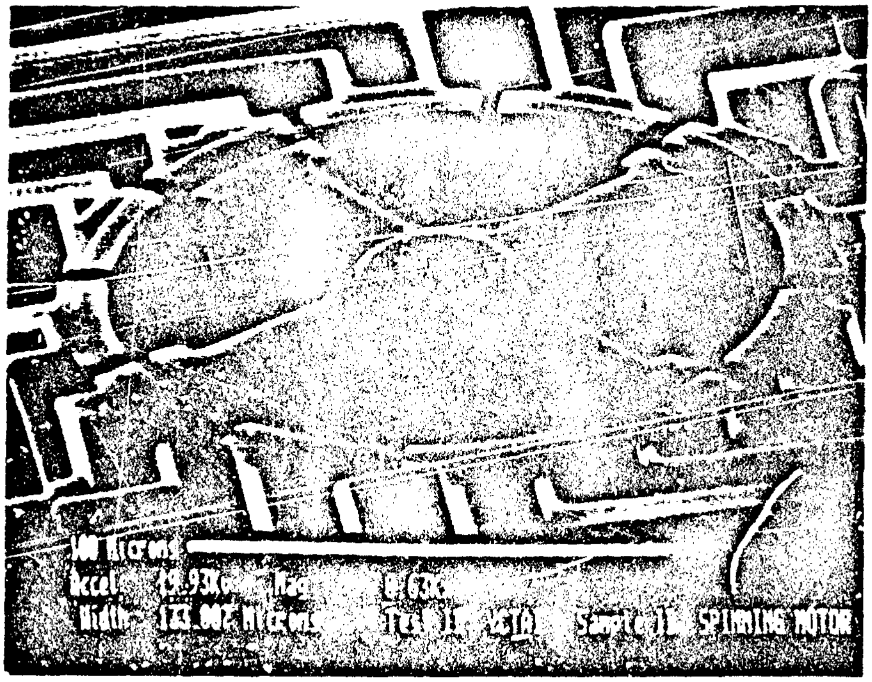
[3]K. D. Wise and K. Najafi, "Microfabrication Techniques for Integrated Sensors and Microsystems," *Science*, Vol. 254, 29 November 1991, pp. 1335–1341.

[4]W.S.N. Trimmer, "Microrobots and Micromechanical Systems," *Sensors and Actuators*, Vol. 19, 1988, pp. 267–287.

[5]H. Fujita and K. Gabriel, "New Opportunities for Micro Actuators," *Transducers '91*, pp. 14–20.

[6]R. S. Muller, "From ICs to Microstructures: Materials and Technologies," *IEEE Micro Robots and Teleoperators Workshop*, November 1987.

[7]S. C. Jacobsen et al., "A Design of an Eccentric Motion Electrostatic Microactuator (the Wobble Motor)," *Sensors and Actuators*, Vol. 20, 1989, pp. 1–16.



SOURCE. R. S. Muller, "From ICs to Microstructures: Materials and Technologies," *IEEE Micro Robots and Teleoperators Workshop*, November 1987

Figure 1—BSAC Rotary Micromotor

motor both makes more efficient use of the Coulomb forces and minimizes the gap width.

The comb drive can be either a linear or rotary actuator. One may think of it as two combs with their tines intertwined but not touching. The stationary comb is given an applied voltage, attracting the drive teeth much like a solenoid. To gain more throw, the frequency of the alternating current (AC) signal applied to the stator may be modulated until a resonant frequency of the actuator is attained. The rotary version, developed at the University of Neuchatel, places the comb teeth at the rotor edge.[8]

While all of these motor types represent large strides in the MEMS field, they all share the deficiency of very low available force and torque. Except for metallic systems with few sliding parts such as the CEM wobble motor and the University of Wisconsin magnetic motor, many of them also experience rapid

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[8]L. Paratte et al., "A Novel Comb-Drive Electrostatic Stepper Motor," *Transducers '91*, pp. 886–889.

wear and short usable lives.[9] As one researcher put it, "Wear may be expected from motors that use sand as the bearing surface." Therefore, lubrication and other tribology issues are among the more important research areas in MEMS, especially for the silicon-based methods.[10]

Bulk Micromachining Technique

The bulk micromachining technique is similar to the sacrificial layer technique in many ways. Its difference is that it typically uses much thicker silicon elements than the standard sacrificial layer technique, and etches these either along specific planes or by employing special doping techniques.

The University of Michigan (UM) has a concentrated effort on single crystal silicon micromachining.[11] Deep cuts may be made along the 1-1-1 plane of the crystal using fairly standard etching techniques, making cuts at angles of 45 degrees relatively straightforward. Cuts at other angles require a two-stage process. In the first stage, boron is diffused into silicon at a controlled rate to create the desired shape. In the second stage, areas that have not been diffused may then be etched away, leaving the doped silicon structure behind. Similar effects may be accomplished using passivating voltages.

Bulk silicon micromachining may allow structures of up to several hundred microns to be fabricated. It may also be possible to overlay layers for even more thickness. However, thicknesses of roughly 20 microns are more common today. Also, very few real mechanical systems have been developed to date using this methodology The University of Michigan has used it for the fabrication of neural probes, such as the example shown in Figure 2, and other sensor-related systems.[12] The University of Neuchatel has used deep dry etching for micromachining accelerometers and various free-standing structures (bridges, cantilevers, etc.).[13]

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[9]L. S. Tavrow, S. F. Bart, and J. H. Lang, "Operational Characteristics of Microfabricated Electric Motors," *Transducers '91*, pp. 877–881; K. Deng, W. H. Ko, and G. M. Michal, "A Preliminary Study on Friction Measurement in MEMS," *Transducers '91*, pp. 213–216.

[10]S. Suzuki et al, "Friction and Wear Studies on Lubricants and Materials Applicable to MEMS," *MEMS '91*, pp. 143–147.

[11]Y. Gianchandani and K. Najafi, "Micron-Sized, High Aspect Ratio Bulk Silicon Micromechanical Devices," *MEMS '92*.

[12]A. C. Hoogerwerf and K. Wise, "A Three-Dimensional Recording Array," *Transducers '91*, pp. 120–123.

[13]C. Linder, T. Tschan, and N. F. de Rooij, *Transducers '91*, pp. 524–527.

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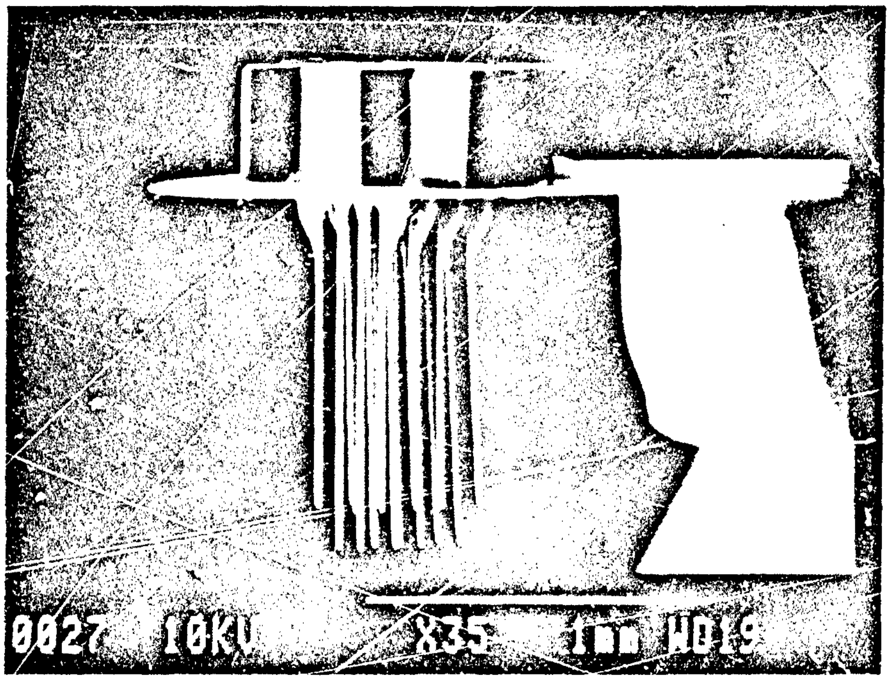

SOURCE Professor K Najafi, University of Michigan

Figure 2—University of Michigan Stimulating/Recording Neural Probe Array

LIGA Process

LIGA is a German acronym for a process translated as lithography, galvanoforming, and plastic molding. It was originally developed to fabricate separation nozzles for the enrichment of uranium.[14] The LIGA process is essentially a method of forming deep microstructures in any number of materials using X-ray lithography and sacrificial layer techniques.

In the United States, the most active organization in LIGA processing is currently Professor Guckel's group at the University of Wisconsin.[15] In addition, Louisiana State University is developing a LIGA facility which will collaborate with the Institute for Micromanufacturing being established at Louisiana Technical University. Professor Guckel has fabricated a number of intriguing systems, including nickel gears, high aspect ratio wobble motors, an electro-

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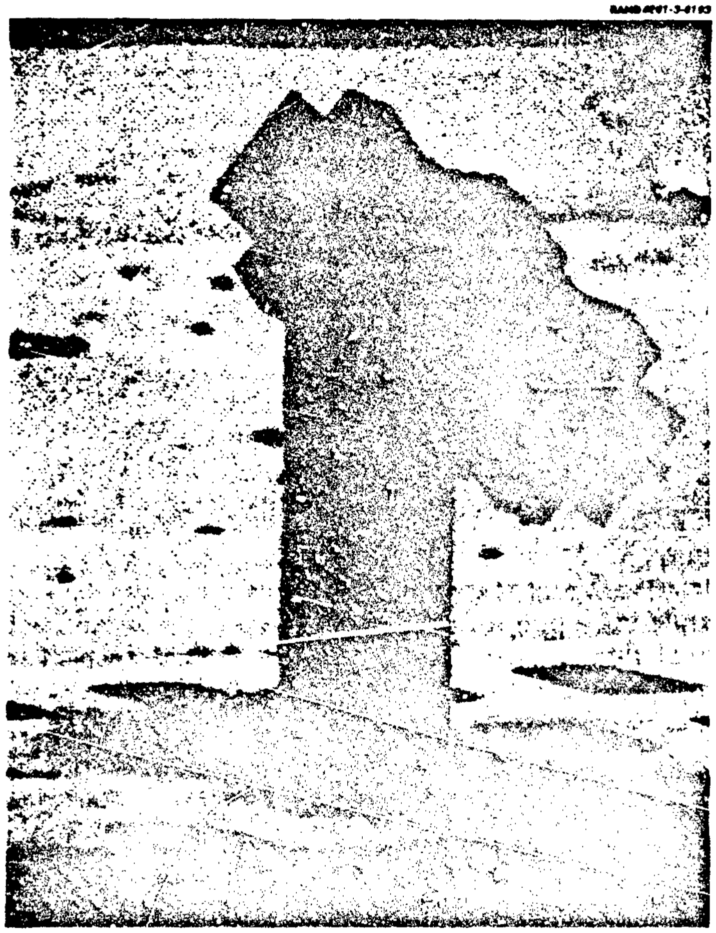
[14]W. Ehrfeld et al., "Fabrication of Microstructures Using the LIGA Process," *IEEE Micro Robots and Teleoperators Workshop*, November 1987

[15]H. Guckel et al., "Deep X-ray Lithography for Micromechanics," *IEEE Solid-State and Actuator Workshop*, June 1990, pp. 118–122.

magnetic micromotor, microresonators encased in hard vacuums, and microrods. A gear mounted on a vertical post is shown in Figure 3.

Several advantages accruing to the LIGA process include high aspect ratio systems (deep relief, as much as 400 microns), very high tolerances along vertical walls (as little as 200 angstroms run out), low temperature fabrication, and the ability to work with a number of materials including transitional metals. These attributes give LIGA the capability of fabricating devices either very difficult or impossible to make using other methods.

There are a number of drawbacks to the LIGA process. The most obvious difficulty is that LIGA requires a very high energy X-ray source such as a synchrotron. The process is therefore more costly and time-consuming than



SOURCE: Professor H. Guckel, University of Wisconsin

Figure 3—University of Wisconsin Electromagnetic Motor and Gears Formed Using LIGA Process

more standard etching methodologies, and few organizations have access to such facilities. However, a number of LIGA researchers are exploring the possibility of using LIGA methodologies to form dies and molds, which may then be used to mass produce microparts.[16]

Other Micromachining Processes

The MEMS field is still quite young. New processes for micromachining are being developed rather consistently. These range from workaday approaches such as electric discharge machining (EDM), to the craftsman's skill of watchmaking, a Swiss approach and advantage, and to esoteric methodologies such as polysilicon fuse and acoustic laser etching.

EDM can be used to form high aspect ratio, metallic structures that do not require exacting tolerances, and electroforming may be applied for thin-walled structures.[17] For example, CED used EDM to fabricate its earlier wobble motors, as shown in Figure 4.

Polysilicon fuse and weld techniques have been used by BSAC, CED, and others to extend the types of mechanical microstructures that can be produced in conventional surface micromachining.[18] These thermal microassembly techniques are especially useful for achieving submicron dimension and increasing the yield of complex structures.

Acoustic laser etching is being pursued at Draper Laboratories.[19] The technique uses sound waves to guide a powerful CO_2 laser over a workpiece. Deep etches made in this fashion can include complicated features like vertical steps and even tunnels underneath a boron doped silicon surface. The process may also be able to machine true three-dimensional structures from solid blocks of materials. Similar efforts are under way in Germany and Sweden.[20]

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[16] W. Menz et al., "The LIGA Technique—A Novel Concept for Microstructures and the Combination with Si-Technologies by Injection Molding," *MEMS '91*, pp. 69–73.

[17] T. Sata, T. Mizutani, and K. Kawata, "Electro-Discharge Machine for Microhole Boring," *National Technical Report* (Japanese), Vol. 81, No. 5, 1985, pp. 105–113; T. Masaki, "Micro Electric Discharge Machining Technology," *Kikai Sekkei* (Japanese), Vol. 34, No. 15, November 1990, pp. 38–42 [translated in *JPRS Report, Science and Technology*, 31 July 1991, pp. 19–24].

[18] G. K. Fedder and R. T. Howe, "Thermal Assembly of Polysilicon Microstructures," *MEMS '91*, pp. 63–68.

[19] T. M. Bloomsten and D. J. Ehrlich, "Laser Deposition and Etching of Three-Dimensional Microstructures," *Transducers '91*, pp. 507–511.

[20] M. Alavi et al., "Laser Machining of Silicon for Fabrication of New Microstructures," *Transducers '91*, pp. 512–515; H. M. Westley et al., "Truly Three-Dimensional Structures Microfabricated by Laser Chemical Processing," *Transducers '91*, pp. 516–519.

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SOURCE: Professor S. C. Jacobsen, University of Utah

Figure 4—University of Utah Wobble Motor

An interesting nonlaser technique being studied at BSAC uses standard sacrificial layer methods, but builds in "flip-up" panels onto the board.[21] This allows quasi-three-dimensional structures to be formed. Many of these micromachining techniques allow a wide variety of exotic coatings to be applied—nitrides, magnetic materials, mirror surfaces, and the like.

Current MEMS Applications

MEMS devices are in operation or will soon be used in a wide variety of sensor and actuator applications. Some of the more prominent applications are listed in Table 3. Virtually all of these examples are research tools or commercial products. The above applications are important to both commercial and military users. However, from a military point of view, while these applications may prove useful and somewhat of an advance, they do not appear to offer real breakthroughs. They are pieces of the puzzle rather than the solution itself.

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[21]S. J. Pister, "Hinged Polysilicon Structures with Integrated CMOS TFTs," *IEEE Solid-State Sensor and Actuator Workshop*, 1992, pp. 136–139

Table 3

A Few Current MEMS Applications

Application	Examples	MEMS Approaches
Accelerometers	U. Neuchatel piezoresistive accelerometers (airbags, aircraft navigation)	Bulk micromachining, silicon mass, photolithography
Speed and position sensors	General Motors magnetoresistive sensors	Molecular beam epitaxy
Pressure transducer	Ford mass air-flow sensor, UM microflow device, BSAC jet printer head	Capacitive diaphram, micromachining, gas, temperature, pressure, flow sensors
Displacement and strain transducers	CED rotary displacement transducer, CED uni-axial strain transducer, field-effect transistor (FET) detector array	Silicon bonding, micropackaging
Electro-optical controls	AT&T fiber optic switching, camera autofocus motor, bubble jet printer	Metallization, etching, piezoelectric motors, microbubble pumps, SMA switches
Chemical and biological sensors	Sandia surface acoustic wave (SAW) sensor (aircraft icing, chemical sensing), UM gas analyzer chip	Piezo quartz plane, capacitive pressure, sensor, pump
Neural probes	UM neural prothesis, central nervous system mapping	Micromachining, microbonding
Medical devices	U. Pisa robotic catheter, U. Minn medical pump, CMU blood flow rotor, CED drug delivery device	SMA actuator, electrostatic membrane, silicon micromachining, micro-incendiaries

SOURCES: R. Howe et al., "Silicon Micromechanics: Sensors and Actuators on a Chip," *IEEE Spectrum*, July 1990, pp. 29–35; R. C. Hughes et al., "Liquid-Solid Phase Transition Detection with Acoustic Plate Mode Sensors: Application to Icing of Surfaces," *Sensors and Actuators*, A21–A23, 1990, pp. 693–699; S. C. Jacobsen et al., "Advanced Intelligent Mechanical Sensors (AMS)," *IEEE Transducers '91*, pp. 969–973; S. C. Jacobsen et al., "Field-Based State Sensing in Micro-Motion Systems," *Third Toyota Conference, Integrated Micro-Motion Systems—Micromachining, Control and Applications*, October 1989; R. Jebens, W. Trimmer, and J. Walker, "Microactuators for Aligning Optical Fibers," *Sensors and Actuators*, Vol. 20, 1989, pp. 65–73; S. A. Jeglinskil, S. C. Jacobsen, and J. E. Wood, "A Six-Axis Field-Based Transducer for Measuring Displacements and Loads," *ASME Winter Annual Meeting Symposium on Microstructures, Sensors, and Actuators*, November 1990; J. Judy, T. Tamagawa, and D. Polla, "Surface-Machined Micromechanical Membrane Pump," *MEMS '91*, pp. 182–186; E. S. Kim, J. R. Kim, and R. S. Muller, "Improved IC-Compatible Piezoelectric Microphone and CMOS Process," *Transducers '91*, pp. 270–273; A. Kourepenis, A. Petrovich, and M. Weinberg, "Low Cost Quartz Resonant Accelerometer for Aircraft Inertial Navigation," *Transducers '91*, pp. 551–553; D. L. Partin et al., "Magnetoresistive Sensors," *IEEE Solid-State Sensor and Actuator Workshop*, 1992, pp. 35–40; S. D. Rappaport, M. L. Reed, and L. E. Weiss, "Fabrication and Testing of a Microdynamic Rotor for Blood Flow Measurements," *Journal of Micromechanics and Microengineering*, 1, 1991, pp. 60–65; N. F. de Rooij, "Current Status and Future Trends of Silicon Microsensors," *Transducers '91*, pp. 8–13; C. H. Stephan, and M. Zanini, "A Micromachined, Silicon Mass-Air-Flow Sensor for Automotive Applications," *Transducers '91*, pp. 30–33; and K. D. Wise, "Integrated Microelectromechanical Systems: A Perspective on the 90s," *MEMS '91*, pp. 33–38.

Most of the applications fall into a few specialized categories—automotive/ aircraft sensors and switches, oil exploration devices, and medical sensors and actuators. Few researchers envision near-term development of microrobots, or even integrated combinations of sensors, actuators, power supplies, and communication means. The limited number of military applications such as missile navigation accelerometers and sonar transducers is a direct extension of the commercial applications.

Typically, a macrosystem is replaced by a smaller, cheaper, more rugged, more reliable, or more sensitive microsensor. These microcomponents should become increasingly essential to the operation of engines, transmissions, suspensions, fire-control systems, and other military vehicle subsystems. However, these applications are typically not stand-alone, integrated systems.

In the next section, we examine posited military systems that would rely upon MEMS as an intrinsic and novel part of the system. In other words, we examine hypothetical systems that only MEMS would make feasible.

3. Posited Military Applications for MEMS Technologies

In the preceding section, the reader was provided some background to generally understand MEMS technologies and approaches. We next explore a few military applications for MEMS technologies. The case study approach was used to extract some of the technology challenges that would face MEMS system developments. Obviously, a case method approach cannot be comprehensive, but we accepted this tradeoff in order to delve into specific technology issues.

The applications in this section are organized, in a loose sense, in order of their difficulty. What we perceive to be the less difficult development tasks are discussed first, and the most challenging systems follow. We present five applications altogether:

- Chemical attack warning sensor
- Identification friend or foe (IFF)
- Active surfaces
- Distributed battlefield sensor net (DBSN)
- Microrobotic electronic disabling system (MEDS)

These five varied applications were chosen because they have apparent military worth, because they rely heavily on the size, cost, and self-containment advantages of MEMS systems, and, sometimes, because they appear to be feasible using current or near-term developmental technologies.

We conclude Section 3 with a brief look at the types of warfare that may be possible if the technology develops to the extent envisioned by many in the field.

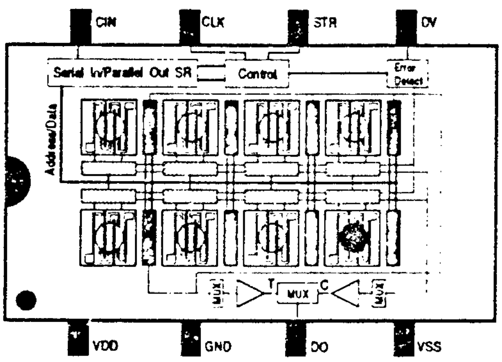
Chemical Attack Warning Sensor

Current U.S. capabilities for detecting noxious battlefield chemicals appear rather limited. For example, in Operation Desert Storm there were reports of the allied forces using a number of German chemical detection vehicles. Currently, MEMS chemical sensors are being developed for the semiconductor wafer industry. It may also be possible to develop chemical sensors for the soldier that inform him of the presence of noxious chemicals.

An example of such a chemical sensor, along with a few desired requirements, is shown in Figure 5.[1,2] Numerous other researchers are also addressing microchemical sensors.[3] The chemical sensor array shown in the left of the figure would measure a few millimeters in both directions. The chemical sensors could be of the adsorptive/desorptive type. That is, the surface catalysts adsorpt chemical species and are periodically heated to desorpt those species at characteristic rates. Theoretically, the desorption rates would be a fingerprint for the type of chemical species involved.

The key advantages that MEMS bring to this application are size and cost. Current man-carried chemical sensors are bulky and expensive, constructed of discrete components. MEMS technology would allow the systems to be button-sized, throwaway modules tailored to the threat. Because of their size, the systems would be able to minimize use of expensive catalysts or biologic media,

Current Technology



Requirements

- Detect chemical agents below harmful thresholds
- Fast detection and alarm
- Low false-alarm rate
- Accurate discrimination of agents
- Low power consumption, battery operation
- Small, lightweight, rugged

SOURCE: Professor J. Schwank, University of Michigan

Figure 5—Chemical Sensor for the Soldier

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[1]Private communication with Professor J. Schwank, University of Michigan, July 1991.

[2]N. Najafi et al., "An Integrated Multi-Element Ultra-Thin-Film Gas Analyzer," *IEEE Solid-State Sensor and Actuator Workshop*, 1992, pp. 19–22.

[3]G. Frye and S. Martin, "Dual Output Acoustic Wave Sensors for Molecular Identification," *Transducers '91*, pp. 566–569; S. W. Wenzel and R. M. White, "Flexural Plate-Wave Sensor: Chemical Vapor Sensing and Electrostrictive Excitation," *Proceedings of the 1989 Ultrasonic Symposium*, 1989.

and might allow detection of a wider variety of substances by a given system. If desired, the MEMS system could also dispense the proper antidote.[4]

To be useful, such a device should meet a number of needs. It should, of course, be able to accurately detect chemical agents below the thresholds at which those agents become harmful to the soldier. It would need to do so rather quickly since the partial pressure of the chemical could build rapidly if the soldier was moving or if there was a strong breeze. The system would need to be reliable for the soldier to trust it. Finally, it should meet all the usual military requirements of ruggedness, long shelf life, ease of use, and so forth.

Identification Friend or Foe

A long-standing problem also observed in Operation Desert Storm is the difficulty in discriminating friendly forces from the enemy during the heat of a battle. Most of today's discrimination aids use reflective tapes, active beacons, or transponders to signal a vehicle's presence. Such systems are extremely vulnerable to interception by the other side, especially in fluid battlefields with intermingled forces.

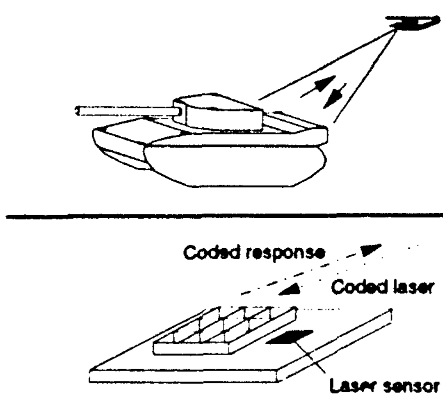
For this reason, one would like a technical aid to the identification friend or foe process. It may be possible to provide such a technical assist using a MEMS system like that shown in Figure 6.

Robert Zwirn, a RAND senior researcher, developed a concept for an IFF system based on macro-sized corner cubes mounted on the surface of a vehicle or mast above it. Here, we extend that concept to millimeter-sized corner cubes scattered over the surface of a friendly vehicle.[5]

Corner cubes have the interesting characteristic of reflecting a spectral glint back to the energy source, a laser beam in our example, regardless of the angle at which the laser beam enters the corner cube. The cubes would normally be covered or otherwise prevented from reflecting until the laser sensor detected a correctly modulated laser query. The coded laser would cause the corner cubes to open. The reflected laser could then be modulated by the corner cube to form a coded response to tell the inquiring system what type of vehicle it was, what

[4]T. M. Studt, "Micromachines: Minature Devices Come of Age," *R&D Magazine*, December 1990, pp. 36–39.

[5]See Appendix A for a first-order analysis on the required size and other characteristics of such a corner cube.



Requirements

- 360° coverage
- Fast response
- Low probability of intercept
- Normally off until interrogated
- Wide spectrum reflector
- Responds to either laser scan or designation
- Low power, battery operated

Figure 6—Identification Friend or Foe

force it was attached to, and so on. The entire procedure would require less than a second.

The system would attain 360-degree coverage by the twin virtues of proliferating the corner cubes over the surface of the vehicle and the reflecting characteristics of the corner cubes themselves. The small size of the corner cubes should assist in their fast response. Low probability of intercept would be ensured by the need for a "key" (coded inquiring laser) to open the corner cubes, which are normally off. The cubes could reflect within specific bandpasses or could be formed of first-surface mirrors to maximize the spectral bandpass. In fact, because of the wide reception angle of the corner cube, they could even be interrogated simultaneously from multiple friendly vehicles.

The major advantages that MEMS provide to this application include:

- *Proliferation across the vehicle*: reduces problems of mud, dust, and laser pointing errors
- *Self-containment*: does not require the system to be connected through armor to vehicle data/power buses
- *Low power drain*: because of minute actuator excursions
- *Fast response*: because of small size and resulting high frequency of actuating elements

As shown in Appendix A, macrosystems of similar design may have problems achieving sufficient dispersion to guarantee reception by inquiring aircraft. The analysis presented there also shows that the minimum size corner cube to

achieve reliable communication is approximately 0.3 mm for a short wavelength (0.5 micron) green light or 1 cm for a long wavelength (10 micron) IR laser. This assumes that the interrogating vehicle is no more than 10 km away, the beam size is 1 sq m, and a contrast ratio is at least 10:1 between signal and background.

Active Surfaces

The concept of designer materials—materials with prescribed and, perhaps, dynamically tunable qualities—could ultimately prove to be one of the most revolutionary MEMS applications.[6] One may envision aerodynamic surfaces with active control boundary layers or armors that act to deflect, break up, or absorb attacking rounds. However, before examining applications that would require a fair amount of power, we looked at an application in which only surface appearance is modified, that is, a camouflage application.

One could envision a number of approaches, including plate orientation, dye pumping, and particle orientation. A surface composed of a number of small plates could possibly orient those plates relative to the observer until a good match with the background was obtained. This would be somewhat similar to the Texas Instruments approach for creating a very-high-resolution television monitor.[7] Another approach would be to pump dyes of various colors and lightnesses to surface pixels. A number of MEMS pumps have been developed by BSAC and other organizations.[8]

A special application of active surface technology is possible with the X-wing experimental aircraft, originally developed by DARPA. This craft is a helicopter that is able to lock its rotor for fast forward flight. During the transition and rotor-locked phases of flight, pressurized air is forced through vents in the leading edge of the blades, producing the Coanda effect for increased lift and stability. Circulation control rotor (CCR) systems also offer advantages in attaining higher speeds and reducing radar cross-section. The prototype version of the aircraft used a CCR with a labyrinth of tubes and valves to control the airflow, resulting in an unwieldy 3000-lb rotor hub. With MEMS technology each vent could be individually and locally controlled. Sensors would determine air pressure, speed, and turbulence and adjust the airflow accordingly. The hub

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[6]T. Takagi, "A Perspective on Intelligent Materials," *First International Conferences on Intelligent Materials*, Kansgawa, Japan, 23–25 March 1992, p. 7.

[7]Gary M. Kaye, "Infinitesimal Wonders to Come," *Photonics Spectra*, July 1991, pp. 64–66.

[8]L. Lin, A. P. Pisano, and A. P. Lee, "Microbubble Powered Actuator," *Transducers '91*, pp. 1041–1044; M. Esashi, S. Shuichi, and A. Nakano, "Normally Closed Microvalve and Micropump Fabricated on a Silicon Wafer," *Sensors and Actuators*, Vol.20, 1989, pp. 163–169.

would then contain only an air plenum along with data and power lines, markedly reducing weight and volume. Local control of the air vents could be used to optimize lift along the length of each blade (this is not done with the current system), smoothing the ride and adding to vehicle agility and power efficiency. Rotor hub complexity would be reduced by eliminating the need for rotor head hinges and hydromechanical actuators. Finally, systems safety would be enhanced through redundancy of actuators and lift command paths, overlapping aerodynamic segments, reduction in numbers of highly loaded dynamic components, and continual system self-monitoring.

In all of these active surface applications, the key aspects provided by MEMS are size, performance, and self-contained operations. The scale of MEMS surface elements is important because a thin, rapidly changeable surface may be needed to match a wide range of sensing bands: infrared, near infrared, radar, and so forth. Self-contained operation is especially important in the X-wing application, so that cumbersome slip rings and centralized control are not required. In fact, it is difficult to see how non-MEMS approaches could work effectively in these latter tasks.

Distributed Battlefield Sensor Net

Modern armies have invested vast sums in developing and fielding systems to locate the enemy. However, in Operation Desert Storm, the allied countries had difficulties in detecting a number of important targets, most famously the Iraqi Scud missiles. From news reports, it would appear that the combined air forces had difficulty in covering the vast area in which the mobile Scud launchers were roaming. We would suggest that search from the air and the ground could be far more fruitful if key terrain points could be monitored continuously. MEMS could possibly help greatly in such a task. We posit a possible solution that we dub the distributed battlefield sensor net (DBSN).

A sketch of the DBSN along with a few requirements are shown in Figure 7. The basic concept is to distribute a large number of cheap and disposable sensor systems over critical areas. They could be seeded by an unmanned aerial vehicle (UAV) or by any number of other means. Once disbursed, a high-flying UAV would locate and record the position of each operating sensor system using a defocused laser and fairly good collection optics. Each sensing system would be provided with a modulating corner cube communication system similar to that discussed for the IFF device, making location possible only through use of a coded laser. The sensing systems would then collect, process, and store data

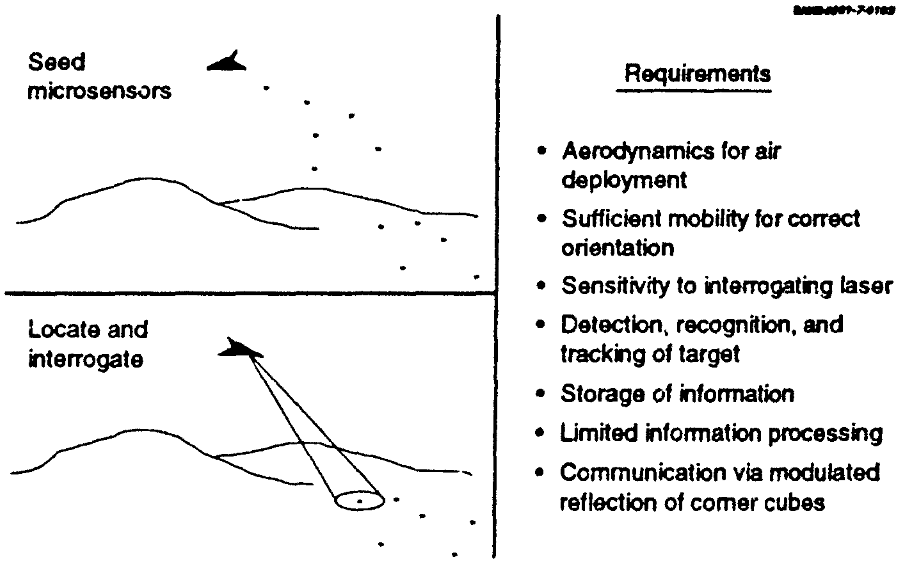

Figure 7—Distributed Battlefield Sensor Net

until interrogated by the coded laser of another UAV. This second UAV could use a less powerful, focused laser with less capable collection optics, making it a cheaper system. Each sensing system would communicate its data back to the UAV by, again, modulating the corner cube.

Appendix A provides a detailed analysis of the sizing and performance of the corner cube reflectors required for a DBSN. The methodology in the analysis is straightforward. Assume a UAV housing a 1000-line sensor (resolution of 0.05 mrad) flies at an altitude of 1 km. Assume that the sensor requires some minimum contrast between the corner cube and background to reliably communicate with the corner cube. Required laser power and corner cube size may then be calculated. For example, a 10-micron CO_2 laser and a conservative contrast ratio between corner cube and background of 10:1 result in a minimum corner cube size of 1.4 mm. This reduces further to 0.3 mm if shorter wavelength (0.5 micron) green laser light is used. Laser power at this interrogation range can be less than 30 mW.

Even the laser itself can be micro-sized. Lincoln Laboratories is exploring development of microlaser diode arrays using chip manufacturing technologies.[9] These arrays differ from laser diodes in that the entire laser is built on the chip.

[9]G. Leopold and N. Munro, "DoD Ponders Big Supply of Tiny Lasers," *Defense News*, 6 January 1992, pp. 22–23.

MEMS component systems would be composed of four subsystems: sensing system, processing system, communication system, and orientation system. The sensing system would be a suite of sensors such as those below. For robustness, several MEMS sensing devices could be defined, each with a different combination of sensors.[10]

- **Thermal.** Short-range, room temperature thermal imaging arrays can be made of MerCad telluride, platinum silicide, InSb, or many different forms of thermocouples and microbolometers.[11] For example, a 32-element, wide-spectrum, imaging thermopile detector of phosphorus doped polysilicon-gold has been fabricated and tested by Baer et al. at the University of Michigan.[12] Honeywell has also shown encouraging results with arrays of microbolometers.[13]
- **Acoustic.** Silicon condenser and piezoelectric microphones show wide range and good sensitivity, even with small apertures.[14]
- **Magnetic.** Sensitive measurement of magnetic field intensity is possible through several different phenomena. A thin film, single axis magnetorestrictive device has been demonstrated by Lenz et al. at Honeywell[15] that can detect a slow moving car up to 100 feet away.
- **Chemical.** Sensing of chemical species ranging from vehicle hydrocarbons to chemical and biological weapons.
- **Nuclear.** Gamma detectors are deemed most important for treaty verification applications. Mercuric dioxide, lead iodide, cadmium iodide, and mercuric bromide have all been recommended for sensing.[16]
- **Radio Frequency.** Millimeter wave radio frequency (RF) appears to be best suited for communicating, receiving, or sensing by micro-sized devices. Dipole or ground-plane antennas could be used for either the 35-mm or 94-

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[10] K. D. Wise and N. Najafi, "The Coming Opportunities in Microsensor Systems," *Transducers '91*, pp. 2–7.

[11] R. A. Wood, C. J. Han, and P. W. Kruse, "Integrated Uncooled Infrared Detector Imaging Array," *IEEE Solid-State Sensor and Actuator Workshop*, 1992, pp. 132–135; T. Kenney et al., "Micromachined Electron Tunneling Infrared Sensors," *IEEE Solid-State Sensor and Actuator Workshop*, June 1992, pp. 174–177.

[12] W. G. Baer et al., "A Multiplexed Silicon Infrared Thermal Imager," *Transducers '91*, pp. 631–634.

[13] R. A. Wood, C. J. Han, and P. W. Kruse, "Integrated Uncooled Infrared Detector Imaging Array," *IEEE Solid-State Sensor and Actuator Workshop*, June 1992, pp. 132–135.

[14] J. Bernstein, "A Micromachined Condensor Microphone," *IEEE Solid-State Sensor and Actuator Workshop*, 1992, pp. 161–166.

[15] J. E. Lenz et al., "A High Sensitivity Mangnetoresistive Sensor," *1990 Solid-State Sensor and Actuator Workshop*, Hilton Head, South Carolina, June 4–7, 1990, pp. 114–117.

[16] Personal communication with Professor M. Reed and Dr. T. E. Schlesinger at Carnegie-Mellon University.

mm windows. For lower frequencies, the device would need to deploy an antenna such as a wire composed of single crystal silicon with a doped conductor.

The communication systems could take two forms. Local intercommunication between devices may involve acoustic "chirping" or RF links. Communication back to command centers could take place with the modulated corner cube approach described earlier. The processing system would essentially record "interesting" data and compress it into a form suitable for communication. The orientation system would provide rudimentary mobility so that the sensor systems can orient themselves with corner cubes facing roughly vertical.

Use of MEMS is again almost essential to this task. Previous macro-sized sensor net systems such as the Remotely Monitored Battlefield Area Sensor System (REMBASS) were found to be expensive, vulnerable, and unreliable. REMBASS (and its predecessor REMS) was used in Vietnam and later upgraded. The RCA-developed system may be emplaced by hand, delivered by artillery, or air-dropped. It is somewhat complex, with separate units for infrared, acoustic, seismic, and magnetic detection, separate communication repeaters, and several types of ground stations.[17]

The advantages of MEMS for deployment and vulnerability would appear decisive. The common sensor chassis for REMBASS weighs some 6.5 lb and measures 8 in. in length.[18] A 155-mm artillery shell carries a single REMBASS sensor or repeater station; conversely, it could carry thousands of MEMS DBSN devices and delivery vehicles. The large number of MEMS devices could then allow the commander to blanket an area with a single shot, or to use micro-sized UAVs for seeding. REMBASS normally has to be precisely positioned, with users checking the sight lines and exactly locating each device. This usually results in use only for perimeter security or deliberate defenses, where there is sufficient time for laydown. This may be why REMBASS is in the table of equipment for only a few light forces and is virtually never used in training exercises, such as those at the National Training Center. MEMS distribution could be much more rapid and complete than is possible with REMBASS, allowing its use in maneuver operations, hasty defenses, and rapid deployment actions.

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[17] *Jane's C3I Systems: 1990–1991*, Section on Intelligence Gathering Systems, Jane's Information Group, Surrey, United Kingdom, p. 256.

[18] *Training Circular 34-1*, Headquarters, Department of the Army, Washington, DC, November 6, 1987.

Scaling down reduces the vulnerability of each sensor. If positioned in the open (as often required for proper system operation), a REMBASS sensor would be visible to soldiers with binoculars at ranges up to 200 m. A 3-mm MEMS device would be invisible for all practical purposes.

Low-cost production is needed for proliferation and redundancy over the battlefield. Once available at throwaway cost, the systems could also be used for minefield marking, trafficability flagging, communications relay, and a host of related tasks. In all of these applications, small size is required for survivability and deployability.

Microrobotic Electronic Disabling System

The reader may note that the sensor net discussed above begins to enter the realm of robotic systems. Each sensor system is fairly autonomous and even possesses the most rudimentary form of mobility. In the application presented here, we assume an almost completely autonomous system.[19] This is obviously a giant leap beyond current technological capabilities; however, respected researchers, primarily in Japan, are pursuing microrobotic studies.[20] For example, Tokyo University has initiated a project to develop an autonomous microrobot.[21]

MEMS are, by definition, small. This points to a fundamental limitation in the use of MEMS themselves as weapons. To have some effect, they must either converge on the target in great masses or they must attack particularly sensitive, but vital, components of the target. It would be a double advantage if these components were themselves reliant upon small systems. Taking these thoughts into account, we decided upon enemy electronics as being a possible type of target against which a MEMS weapon may be used, and we developed a concept for a microrobotic electronic disabling system (MEDS).

The basic MEDS concept is outlined in Figure 8. MEDS are seeded in the general vicinity of the target. They would then sense the location of electronics, move to

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[19] A. M. Flynn, "Gnat Robots (and How They Will Change Robotics)," *IEEE Micro Robots and Teleoperators Workshop*, November 1987.

[20] K. Suzumori, S. Iikura, and H. Tanaka, "Flexible Microactuator for Miniature Robots," *MEMS '91*, pp. 204–209; K. Suzuki and F. Chikafuji, "Six-Legged Robot with Flexible Micro-Actuator," *Sensor Technology* (Japanese), Vol. 11, No. 12, December 1991, pp. 34–37; S. Tachi, "Sensors and Sensing Systems in Advanced Robotics," *Transducers '91*, pp. 601–606; K. Kuribayashi et al., "Micro Flexible Robot Using Reversible TiNi Alloy Thin Film Actuators," *JPRS Report, Science and Technology*, 24 July 1992, p. 55; K. Inagaki, "Choosing Micromachine R&D Themes," *Kikai Sekkei*, Vol. 34, No. 15, November 1990, pp. 32–37 [translated in *JPRS, Science and Technology*, 12 June 1991, pp. 10–18].

[21] T. Yakasuda, *JPRS Report*, 1 August 1991.

that location, infiltrate the system, and disable it. There can be no doubt that this is a tall order. We present an outline of the concept below.

As shown in Figure 8, the MEDS would be seeded into the general target vicinity in a manner analogous to the DBSN discussed above. Accurate and timely placement of the MEDS devices, rather than indiscriminate coverage of an area, appears to be important for cost, payload, and time reasons. For example, assume there are 50 target areas, each 300 meters square, in a region 100 km square. Further assume the MEDS devices can move tens of meters, and that 15 to 20 devices should be within local movement range of a target system. If the entire 100 x 100 km area is seeded, approximately one billion devices would be needed. If only road networks spaced 5 km apart were covered, the number would reduce to approximately 13 million. If the 50 target areas alone were seeded to the same level, only 20,000 devices would be needed. Concentrating on specific target areas would also strongly reduce the delivery time. A 100-knot UAV might take four to five days to cover the entire 100-sq-km region, but only four to five hours to service 50 target areas.

It therefore appears desirable to dispense MEDS as near to the target as possible to keep required systems to a reasonable number. One dispensing scheme would use UAVs to fly to the target vicinity. The UAV would then dispense small canisters that would power to the target (aerobot), glide via a parafoil, or arrive

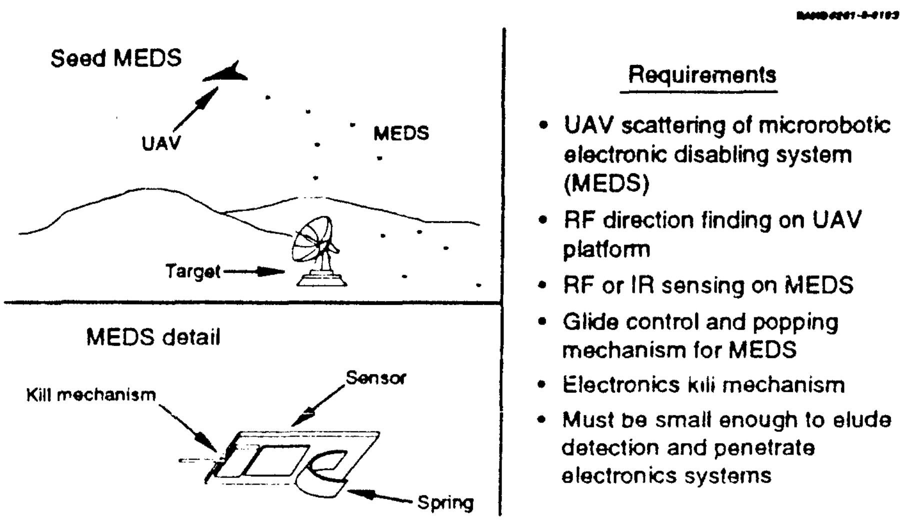

Figure 8—Microrobotic Electronic Disabling Device

by other means. The canisters would move to within a few meters of the target and dispense the MEDS. The MEDS would then move to and infiltrate the target.

One could envision an airborne microrobot[22] or one using various forms of "insect-like" motions.[23] Another possible mechanism for MEDS locomotion would be a flea-like motion. The MEDS would pop up to some height and then glide in the desired direction. Obviously, it would be advantageous to place the MEDS upwind of the target. A rough calculation of the energy and energy mass requirements for locomotion is shown in Appendix B. Here, a flat, 3-sq-mm MEDS device is assumed. We further assume 1000 launches to a height of 2 m. We assume that the MEDS is not aerodynamically efficient but that it can orient itself during launch to minimize its attack angle, giving it a drag coefficient of roughly two. Lastly, we assume that the MEDS is chemically launched using a high-energy self-oxidizing propellant such as a low-flame-temperature double-base nitrocellulose/diglycol dinitrate propellant, which has a specific energy of 3 kJ/g. With a 30 percent efficiency in energy conversion, 1000 launches would then require 0.026 mg of propellant. This would be 2.4 percent of the weight of the MEDS device and occupy 3.8 percent of its volume.

Each MEDS device itself would consist of five subsystems:

- Sensor system
- Processing and autonomous navigation
- Kill mechanism
- Mobility system
- Communication system
- Power system

The sensor system would be optimized to acquire electronics from the distance of a few, perhaps tens, of meters. The system would need to move to and infiltrate the target. It could move via a variety of methods such as the flea-like motion already discussed. The kill mechanism could consist of spraying a caustic or conducting fluid. Development of a kill mechanism, a primary challege for a MEDS device, is distinguished from other subsystems in that the kill mechanism cannot be developed generically, but rather must be developed in response to

[22] S. B. Crary, G. K. Ananthasuresh, and Sridhar Kota, "Prospects for Microflight Using Micromechanisms," *Proceedings of the Japan Council's International Symposium on Theory of Machines and Mechanisms, September 24–26, 1992*, Nagoya, Japan.

[23] K. Suzuki, et al., "Creation of an Insect-Based Microrobot with an External Skeleton and Elastic Joints," *MEMS '92*, pp. 190–195.

specific targets. The system could employ a corner cube for external communication, although this would not suffice for communications with other MEDS. For this, perhaps some sort of acoustic chirping or other mode of communication could be used that uses the system's on-board sensors. Lastly, the system would require a fair amount of power compared with previous applications.

Insect Platforms

MEDS, obviously, presents a combination of rather daunting technological challenges. Three of the more difficult tasks are everyday even to insects: navigation, mobility, and power. Rather than try to recreate these capabilities, one option may be to harness insects as platforms for MEDS.

Researchers at the University of Michigan have been developing neural probes for over a decade. These probes may be either stimulating or recording. The probes themselves interact directly with the dendrites in the central nervous system (CNS) of the test subject. They have been used successfully to map the brain of various organisms. For example, researchers at the University of South Hampton have almost completely mapped the CNS of a honey bee using neural probes. Generally speaking, the procedure consists of stimulating a synapse and then recording the response elsewhere within the CNS.

One could envision using stimulating neural probes in conjunction with microsensors and processors to direct an insect platform in the desired direction by using straightforward Pavlovian stimuli; the insect would be either rewarded or punished directly through its CNS depending on its actions.[24] It should be evident that the small scale of MEMS technology is required here, both in terms of connection dimensions and payload considerations. The MEDS sensor and on-board processor determine the desired actions and deliver commands (punishment or rewards) to the insect platform, thereby arriving at, infiltrating, and disabling the target.

One may be able to use the insect as a power source, like a self-winding watch or via other means. The kill mechanism could also stem from the insect. For example, one could dope a spider's web with a conductor.

Development of such a system presents any number of problems. How could the neural probes be efficiently married to the insect CNS? Are insects sufficiently

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[24]One could also envision the use of biologic components. See for example, N. Kami-ike et al., "Characteristics of an Ultra-Small Biomotor," *MEMS '91*, pp. 245–246.

responsive, even given direct stimuli? Such a system may prove expensive since the mating of MEMS devices to insects seems unlikely to lend itself to mass production. More directly, nothing quite like this has ever been attempted, and it may simply prove infeasible.

MEDS Warfare

One could imagine MEDS being used as a battlefield weapon to disable enemy electronics. However, because the MEDS will most likely need to be dispensed in a relatively accurate manner, it is difficult to posit how MEDS could be a more effective "munition" than any number of other warheads.

The utility of MEDS in a countervalue role is more obvious. By disabling the electronics of critical targets, a modern economy could be severely damaged with minimal loss of life and minimal damage to the non-electronic portion of the infrastructure. If combined with a blockade or economic embargo, such damage would likely prove unacceptable to most modern economies. Strategic targets vulnerable to MEDS would include:

- Power plants/relay stations
- Transportation grid nodes
- Airports
- Seaports
- Switching yards
- Major freeway intersections
- TV/radio stations
- Telephone exchanges
- Computer/research centers
- Electronics denial at key production sites

MEDS, if feasible, would therefore offer military planners and political leaders a weapon yielding strategic gains within politically acceptable constraints.

We end this subsection with one concern. MEDS could develop into a trump card for the United States; however, the United States is not projected to be a leader in the MEMS field. If MEDS were to prove feasible, enabling technologies would more likely be developed elsewhere. In addition, once (if ever)

developed, such a weapon would appear ideally suited for terrorist actions.[25] For these reasons, it may be at least as important for the United States and other industrialized countries to develop countermeasures to MEDS and other microrobotic weapons if such weapons ever materialize.

As a minimum precaution, the United States should monitor the development of MEMS technologies with an eye toward the types of weapons that may become possible with those technologies in order to either pursue weapons development or to develop countermeasures to them.

Simulations

Many of these applications may be examined using simulation. Computer-aided design (CAD) systems such as CAEMEMS[26] and MEMCAD[27] are now being used for device design (force levels, dimensions, sensitivities, etc.). A high-resolution geographic information system (GIS) may be used to determine resolutions and ranges required for DBSN and MEDS detection. A GIS may also be helpful for ascertaining active surface contributions to survivability. SIMNET, JANUS, or other force-on-force simulations may be used to roughly determine the operational impact of IFF, DBSN, and MEDS systems on the battlefield. SIMNET should be especially helpful in looking at micro-UAVs as MEDS delivery devices and as communication interrogation platforms and relays.

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[25]We are not predicting that a MEDS weapon, however seemingly ideally suited, would necessarily be used as a terrorist weapon. For example, chemical and biological weapons would also seem ideal for terrorist activities, but these weapons have not, in fact, gained wide usage among terrorists.

[26]Y. Zhang, S. B. Crary, and K. D. Wise, "Pressure Sensor Design and Simulation Using the CAEMEMS-D Module," *IEEE Solid-State Sensor and Actuator Workshop*, June 1990, pp. 32–35.

[27]R. M. Harris and S. D. Senturia, "A Solution of the Mask Overlay Problem in Microelectromechanical CAD (MEMCAD)," *IEEE Solid-State Sensor and Actuator Workshop*, June 1992, pp. 58–62.

4. How to Proceed from Here: Views from the MEMS Community

In the course of addressing military applications for MEMS technologies, we spoke to a number of leaders within the MEMS field. Most of these distinguished researchers held strong opinions as to the best direction for the U.S. community to pursue in developing the MEMS field. In bringing these views to the forefront, we asked a simple question, which may be paraphrased as, "What type of MEMS development program would you pursue if you were in a key government position and able to formulate the ideal program?" As may be seen in Figure 9, although there was agreement within the community on some important issues, the responses to this question were characterized by their divergence.

The implicit understanding was that the views of individual researchers would be kept confidential. In Figure 9, we therefore identify individual researchers by number only. We did not seek to restrict responses to the topics listed along the top of the figure. These headings arose naturally during the course of our inquiries. The first five columns indicate the overall organization of a MEMS program. A check indicates researcher support for that particular view.

A check in column 1, the "Applications" column, denotes that researchers believe that a MEMS program should be applications oriented. Note that there was near universal acceptance of this opinion. Many researchers noted that MEMS technology has produced some fascinating devices, but what is really needed is a compelling application. They felt that MEMS must be demonstrated to solve some problem that is unresolvable with any other technology. Some researchers felt that such a demonstration must be made within a couple of years, or all of the recent interest in MEMS research may fade, at least in the United States. A number of researchers pointed to the field of artificial intelligence as an example of this phenomenon—a continually promising but rarely delivering field.

Two of the researchers who felt that any future MEMS program should be applications oriented also felt that it should concentrate on basic research (see column 2). One of these researchers also held the view that the MEMS

Researcher	Applications	Basic research	Consortia	Competitive	MOSIS (see text)	No. of projects	Disbursement	Infrastructure $	Project $
1	✓	✓		✓		A few	U, S	?	100
2		✓	✓		✓	3 or 4	U	3	6 or 8
3	✓		✓		✓	7 or 8	U, C	1 to 2	8 to 10
4	✓			✓		20+	U, S, G	0	10 to 15
5	✓			✓		?	U	?	5 to 10
6	✓			✓		5	U, C	10	10
7	✓					6	U	1	3
8		✓		✓		18	U	0	1 to 2
9	✓			✓		?	S	1	?
10	✓	✓	✓			?	U, C, G	2	10 to 15

($ in millions per year)

U : University C : Major corporation
S : Small business G : Government lab

Figure 9—The Ideal MEMS Program: Views from the MEMS Community

community needs a large influx of research monies, which somewhat alleviates this apparent contradiction. The researchers who stated that basic research was the primary need generally held that the field was now too immature to promise some dramatic application. An applications-oriented program may hold greater risk in that it could simply produce a high-visibility failure.

Researchers held by an almost two to one margin that a MEMS program should be competitive rather than cooperative, especially if that cooperation were to take the form of consortia. Consortia were considered bureaucratic and stifling. Some claimed that a consortium benefits the leading institution at the expense of other members. Of those who backed the cooperative approach, two specifically recommended a MOSIS-like fabrication agreement. MOSIS is a consortium of universities administered by the University of Southern California (USC). Universities and other smaller research institutions send designs to USC for semiconductor chips. These chip designs are then grouped together and placed for bid to industrial firms that have agreements with MOSIS. One of the key ingredients that makes this process work is that universities must follow strict design guidelines, thus ensuring fabricability at reasonable cost. An argument for a MOSIS-like agreement within the MEMS community would be that organizations with limited access to fabrication facilities would be able to

contribute to MEMS research. Most of those opposing consortia specifically oppose a MOSIS-like operation at this time. Their argument is that the MEMS field is too immature for design standards to be set, and that a MOSIS-like agreement would discourage fabrication innovation.

The area in which researchers disagreed most was in the actual structure of a MEMS program. We categorize their opinions on program structure into four areas:

- Number of participating institutions
- Types of participating institutions
- Infrastructure investment
- Project investment

An area of agreement was that almost all researchers held that universities should be key players in any successful MEMS program. The reason for this goes beyond the fact that most researchers we spoke with are university professors. With a few notable exceptions, the most innovative MEMS research conducted within the United States has been conducted by universities. Universities house the greatest talent within the field, and a number of them have excellent facilities for this type of research. Other than universities, we found little consensus for research activities in other types of facilities such as small business, large corporations, or government laboratories.

A number of arguments were presented both for and against various types of institutions. The argument presented for small business was that it is efficient and innovative. Against small business is its lack of facilities and personnel. Large corporations were said to be well equipped, but wasteful and risk adverse. Hardly anyone mentioned government laboratories; those who did tended to lump them in with large corporations.

The issue of program funding elicited a few surprising responses. The range spread from $1 million per year to $100 million per year, with a slim majority of researchers citing figures near the $10 million per year range. We had expected the community to voice a funding need similar to the first-tier efforts of other countries—in the $100 million per year range. Instead, most of the researchers stated that the field was talent limited. This implies that, with only a limited pool of talent, disbursing funds outside of that pool would be a waste of money.

Divergent views were also given on the issue of infrastructure funding. Some researchers felt that no new infrastructure or fabrication facilities were needed. Indeed, one analyst claimed that MEMS research could be carried out in a garage

with equipment donated from industry. On the other hand, other researchers would like to see a fair amount of infrastructure investment, believing that the community has only scratched the surface of possible MEMS fabrication techniques. A slim majority expressed the view that only a few pieces of equipment here and there could be put to profitable use.

A few of the community's views noted above deserve comment. First, although the U.S. MEMS community may not possess unlimited talent, it currently leads the field primarily because of the excellent talent within the United States. Therefore, since other countries consider themselves sufficiently endowed with research talent to effectively spend $100 million per year on MEMS programs, we fail to perceive the factors unique to the United States that prevent it from doing likewise. The Japanese, for example, seem to be progressing at a remarkably rapid clip, beginning from a talent base smaller than that in the United States.[1] Second, although some of the best talent within the field is currently within the universities, we do not believe that this precludes others from successfully entering the field. Especially in light of the recommended emphasis on an applied MEMS program, it would appear desirable for business—large, small, or midsized—to broaden its involvement. Last, we do not fully understand the argument of how some sort of collaborative fabrication effort, be it MOSIS-like or similar to some other organization, would stifle innovation at facilities that possess their own fabrication equipment. It appears to us that both efforts could coexist; those without facilities would make do with the collaborative arrangement, and those with facilities would make their own efforts.

Before one can posit a government program for the development of military MEMS technology, he must first identify a goal. One possible goal, as already stated, would be to develop an application that demonstrates the unique capabilities of MEMS technologies. We agree that this would indeed be a desirable goal; however, we do not perceive that such an application has been identified. We have posited a few applications here, but they hardly constitute an exhaustive survey of the possibilities. We would therefore recommend that

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[1]For example, Tokyo University has initiated a project to develop an autonomous microrobot, as reported by Takashi Yasuda, et al "Study of Micro-Mechanisms," *JPRS Report, Science and Technology*, 1 August 1991, pp. 85–88. There is no parallel effort to this in the United States. In the same issue of *JPRS Report*, another paper describes Japanese efforts in electro-discharge micromachining, an area in which Japan clearly leads. A good perspective on Japanese activities may be had from the 20 May 1991 edition of *JPRS Report* entitled, "Perspectives of Micro-machining Technology." This is closely followed (12 June 1991) by a more technical *JPRS Report* edition entitled, "Micro Machining Technology." Also, the Japanese recently hosted the First International Conference on Intelligent Materials, which featured a large number of MEMS approaches. Although "international," the vast majority (if not all) of the papers originated from research in Japan. The Japanese have also been well represented at MEMS conferences, with the 1991 MEMS conference being held in Nara, Japan (see *IEEE Proceedings*, Catalog No. 91CH2957-9).

more attention be given to selecting appropriate applications at the outset of any government program.

Once target applications are defined, a technology development effort can begin to address key technology areas. For example, one of the limiting technologies for a number of applications may be power sources. It would therefore be necessary to develop power sources to some specified level before applications dependent upon them can be pursued.

As the analytic and technology development efforts progressed, applications projects could then be pursued. Target applications would preferably be systems that relied upon MEMS technologies for their basic functions. Getting to this point should not be allowed to become a long, drawn-out affair. Program managers should be willing to accept a fairly high level of risk. However, simply jumping into an application development program with little or no preliminary research would be unnecessarily risky.

The types of applications that should be pursued would probably be a function of the government organization involved in the development. For example, one would imagine the Army to be more interested in pursuing an IFF device than a submarine tracer. However, much of the basic technology could cut across applications. Returning to our example, one could envision the IFF device and the submarine tracer both using the corner cube concept discussed earlier.

In addition, much of the research necessary for the development of military applications should also prove of use within the civilian sector. For example, a distributed sensor net may offer possibilities for inexpensively monitoring seismic events over a broad region. For these reasons, we would recommend that as much research as possible be kept unclassified to facilitate communication throughout the community. Of course, as an application development progressed, national security considerations could eventually be expected to override the benefits of open communication, but this point should be delayed until absolutely necessary.

In addition to fostering development by making research as open as possible, the government should also encourage more organizations to enter the field. This would happen rather naturally if government expenditures in the area were to rise, but some relatively small portion of funds could also be set aside for facilities. We are not recommending that the government build new MEMS fabrication facilities, but we would suggest that a program be undertaken to broaden the availability of current facilities. For example, a share of facilities time could be leased from, say, the University of Michigan or the New Jersey Institute of Technology, which the government or some agent would then sublet

to small business. This may not be the best approach, but certainly, some program should be undertaken to broaden access to facilities.

A remaining issue is that of the overall size of a government program or programs. The amount of investment required is of course a function of the goals. Looking at the MEMS field from a larger sense, one goal could be to make the United States one of the first-tier investors within the MEMS field. This would imply an overall investment in military and domestic MEMS technologies of some $100 million per year. If one assumes that not much more research funding will be forthcoming from the U.S. government for civilian applications and that industry may be expected to at least match government investments, U.S. military research organizations would need to fund MEMS activities at roughly $50 million per year.

5. Final Observations and Recommentions

In presenting a number of the concepts outlined in this report, we encountered no researchers who would state that any of the concepts were impossible. In fact, the posited applications normally triggered a lively discussion on how to best achieve them. This is not evidence of the inevitability of devices like these, but rather a suggestion of the potential MEMS technology represents. This should give pause to those involved in making military policy, particularly policy relating to the national technology base. Given the wide discrepancy between funding in the United States and abroad, the lack of a more aggressive policy on the part of the United States would make it only a matter of time before the United States loses its lead in this field, if this has not occurred already.

Therefore, it would seem prudent to at least monitor the field, taking note of advances or breakthroughs which may yield significant military gains. If and when such advances occur, the United States, as a minimum, should be concerned with possible countermeasures to what may in the future pose measurable threats to U.S. national security.

As an activist measure, we would further recommend that the Office of the Secretary of Defense and the military branches develop and pursue reasonable target applications of MEMS technology for demonstration in the three- to-five-year time frame. Such efforts would allow the military to truly assess the military potential of the technology. Even if some of the efforts fail, as would be expected from their high-risk nature, a modest activity of this kind would allow the military to capitalize on unforeseen breakthroughs that may come from military, civilian, or foreign research.

Appendix A
Corner Cube Performance Calculations for IFF and Distributed Battlefield Sensor Net Applications

Robert Zwirn

Summary

This appendix provides an initial analysis of the performance of RAND's modulated corner cube concept in both IFF and distributed communication net applications.

In general, the conservative calculations here provide confirmation of effective operation with:

- **Reasonably sized lasers** (those designators already deployed in the case of the IFF application, and tens of milliwatts for the application that locates micro-sized cubes), and
- **Reasonably sized cubes** (on the order of a centimeter) or arrays of cubes.

We derive general relationships for the cube's signal-to-background ratio, and then give IFF examples for various wavelengths and cube dimensions.[1] Possible modulation frequencies are discussed. A UAV example shows how elements of a distributed net can be located for subsequent interrogation. Following a short discussion about arrays of microcubes, examples of signal power requirements are computed.

The appendix is written in a tutorial manner. The calculations are intended to provide an order of magnitude sense of performance. Certainly, a detailed analysis should be undertaken as a prelude to any further investigation. Comments are interspersed to put the numbers into perspective. The treatment is limited to the salient aspects of an airborne sensor's capability to reliably detect

[1]Classified aspects of the cube's use are not discussed here. Generic parameter values are used to avoid revealing actual values.

returns from macro-sized corner reflectors, micro-sized reflectors, and arrays of reflectors at maximum range.

The author is grateful for the expert suggestions and refinements provided by his RAND colleagues Jon Grossman and Lloyd Mundie.

Background

Conventional illuminated corner cubes have the useful property that they reflect energy directly back at the source of illumination over a large range of incidence angles, approaching ± 45 degrees per corner. An assembly of four back-to-back corners allows illumination from anywhere within the four quadrants of a hemisphere. (Redundant assemblies, which are skewed 45 degrees with respect to each other, complement each other by providing strong returns at just the angles where weakness would otherwise occur.) There is some spreading of the energy due to diffraction, as in any optical system.

Conversely, competing energy reflected back toward the source from the cube's cluttered surroundings spreads in all directions, as described by Lambert's law. Therefore, the corner's return is very strong, in a signal-to-clutter sense. It is also very directional.

Competing receivers, which are not collocated with the source, receive essentially no signal, thus providing a very secure communication link with very little power required at the source of the information. This is because the receiver is collocated with the illuminator, which provides the power. Many spatially separated illuminators can simultaneously be serviced by a single corner cube without any mutual interference. Moreover, many widely disparate wavelengths from different locations can simultaneously be serviced by a single corner cube without any mutual interference.

Well-known applications of such conventional corner cubes include radar reflectors for nonmetallic sailboats (enabling rescuers to find them) and precision alignment of optical equipment (lasers, reticles, collimators, and telescopes).

Basic Calculations

An effective corner cube must meet two requirements for signal strength and two for beam divergence:

The signal-to-background (S/B) ratio must be adequate.

The signal-to-noise ratio (SNR) must be adequate.

The return beam must be large enough to ensure filling the sensor aperture.

The return beam must be small enough to prevent interception by another's sensor.

Derivation of the Equation for S/B

Assume apertures and spots have generic diameter D (neglect the $\pi/4$ distinction between square and circular apertures). Assume that the background has the same reflectance as the corner, to provide conservative results.

Let

D_{1p} = diameter of the laser-illuminated patch at range R
E_{tar} = irradiance of the target (patch) by the laser
D_s = diameter of the sensor aperture
θ_s = angular resolution of the sensor = $2.44\ \lambda/D_S$
r_s = linear resolution of the sensor at range = $\theta_s R$
E_{sc} = irradiance of the sensor by the corner's reflected beam
E_{sb} = irradiance of the sensor by the background's reflection
A_c = area of the corner
D_c = diameter of the corner
θ_c = angular resolution of the corner = $2.44\ \lambda/D_c$
D_{cp} = diameter of the corner-illuminated patch back at the sensor = $\theta_c R$
$e^{-\alpha R}$ = attenuation factor due to atmospheric patch length, R

The irradiance of the sensor by the corner's reflected beam is:

E_{sc} = energy reflected $\cdot$ path loss/area illuminated

$$E_{sc} = \left(E_{tar}\,A_c\right)e^{-\alpha R}\Big/\left(D_{cp}\right)^2 = \left(E_{tar}\,D_c^{\,2}\right)e^{-\alpha R}\Big/\left(2.44\,\lambda R/D_c\right)^2 \qquad (1)$$

The irradiance of the sensor by the background's reflection is:

E_{sb} = energy reflected $\cdot$ path loss/area illuminated

$$E_{sb} = \left[E_{tar}\,(D_{1p})^2\right]e^{-\alpha R}\Big/\left(2\,\pi R^2\right) \qquad (2)$$

Therefore,

$$S/B = E_{sc}/E_{sb} = 1.055\ D_c^{\,4}\Big/\left(D_{1p}^{\,2}\lambda^2\right) \qquad (3)$$

This result is intuitively pleasing. It is:

Independent of range: R

Independent of atmospheric attenuation: $e^{-\alpha R}$

Independent of sensor aperture diameter: D_s

Notionally, the relationship can be considered the product of two effects: the fraction of the energy the cube initially intercepts:

$$D_c^2/D_{1p}^2 = A_c/A_{1p}$$

and the concentration (inverse of diffraction) of the beam it reflects (squared to produce a solid angle):

$$D_c^2/\lambda^2 = 1/(\lambda/D_c)^2 = 1/(\text{spreading})$$

Basic Calculations for a Hypothetical IFF Application

Consider an aircraft designating a 3-m × 3-m tank at 10 km. To have an IFF problem in the first place, there must be enough energy returned to the aircraft from the body of the tank for a missile to lock on to, even though the energy has traversed the atmospheric path to the tank and back. This path is common to both the tank and the competing cube, as is the illuminator wavelength and the aperture of the receiver. Assume that intercepted energy is subsequently reflected and spread over an area of 1 m^2 at the plane of the aircraft. This is consistent with the illuminator and the sensor both being in the same turret.

To bound the result, let us compute S/B if λ is very small, say 0.4 µm. Also define the 1-m spot size to be between the zeros of the pattern, not some other figure of merit conventionally used to describe the energy between 1/e, or half peak points, or the like. Assume the laser patch matches the tank with a dimension of 3 m. The angular subtense of the patch is:

$$\begin{aligned} D_{cp}/R &= 2.44\ \lambda/D_c \\ 1\ \text{m}/10^4\ \text{m} &= 2.44 \cdot 4 \cdot 10^{-7}/D_c \\ D_c &= 0.976\ \text{cm} \end{aligned}$$

From Eq. (3):

$$S/B = 1.055\ (9.76 \cdot 10^{-3})^4/[3^2\ (4 \cdot 10^{-7})^2] = 6647$$

The corner provides over three orders of magnitude greater signal than the tank (the cube's background). A smaller cube would intercept less energy initially and subsequently cause a greater spreading because of divergence. These parameters can be adjusted because we have over three orders of magnitude of margin to exploit.

Before going on to demonstrate the effects of modifying wavelength and cube dimensions, we will touch on modulating the return.

Modulation

The spectrum of applications starts with the efficient exploitation of presently deployed systems and extends to future systems specially designed for unique interrogation applications. For instance, an existing sensor (which was designed to detect the background return of a laser designator) can easily detect the presence or absence of a return orders of magnitude stronger. The cube's modulation can be programmed to be compatible with any of the kinds of sensors on board, including the missile seeker itself. Several methods of modulation are available—from switching the transmission of a cube's liquid crystal window on and off at tens of cycles per second to piezoelectric transducers that can operate into the tens of kiloHertz to intermittently spoil the cube's precise right angles.

A simple example is to use the deployed on-board seeker head that was designed to respond to the return from the laser-illuminated background. As long as the cube frequency and the designator frequency are sufficiently dissimilar, the seeker circuitry will respond differently to the cube's on and off states. This response can provide an input to a simple demodulator located inside the aircraft or the seeker. Alternatively, if the return is in-band for an on-board sensor (which is displayed on a standard monitor), a simple window gate in the center of the field of view can drive a demodulator. The cube simply turns on and off at a 30-Hz or 60-Hz rate. A 10-bit "code word of the day" can be repeated three or six times in a second to stave off the attack. The length of the word and the bit rate depend on the specific on-board system and requirements for code security.

Subsequently, future sensor/illuminator/cube systems can be optimized for extracting a particular format of information from a modulated return.

Alternative Wavelength Possibilities

Consider a wavelength longer than the first example: for instance, 25 times longer (10 μm). To maintain the same divergence

$$D_c = 0.976 \cdot 25 \cdot 10^{-2} \text{ m} = 24.4 \text{ cm}$$

The S/B increases by 625 to 4,134,444, more than sufficient energy margin. If instead, the cube would have remained fixed in size at 0.976 cm while the wavelength increased by 25 times to 10 μm, then the divergence angle would have increased and the energy density at the receiver would have been reduced by 25^2. The cube would have returned

$$S/B = 6647/25^2$$
$$S/B = 10.63$$

Specification of false alarm and dropout probabilities would drive the actual S/B design figure.

Equivalently, if the cube for the short wavelength signal at 0.4 μm were intentionally made smaller by a factor of 25, it would still provide 10.63 times more energy than the tank.

$$D_c = 0.976 \text{ cm}/25$$
$$D_c = 0.39 \text{ mm}$$

These results demonstrate that the energy spreading via Lambert's law is so great that even a very small corner reflector can return many times more energy to the vicinity of the illuminator than the background.

The difference can be reliably discriminated by the receiver. If it had sufficient signal-to-noise ratio to initially discriminate the reflected tank spot from its own receiver noise level, then it can certainly discriminate this even larger signal (the difference between the corner return and the tank return) from that same noise level. Specification of false-alarm and dropout probabilities would also drive the

actual SNR design figure. The signal-to-noise ratio is elaborated upon in subsequent calculations.

Increasing the corner cube size has the benefit of providing an enormous amount of return energy compared with that required. Alternatively, decreasing the cube size increases the beam divergence and therefore the probability of interception of an otherwise covert beam. For most airborne scenarios some reduction is acceptable. For ground-based designators it is not. They would become beacons and therefore vulnerable targets. To be conservative, we require components of conventional size. From a practical standpoint, smaller components are more sensitive to dirt and mud, whereas excessively large components become good targets in and of themselves (expensive ones too).

Basic Calculations for Locating a Micro-Sized Corner Cube in a Distributed Net Application

Consider trying to accurately locate a miniature corner cube within a large area illuminated by an airborne laser. The illuminator is painting the ground, while a sensor is determining the coordinates of returns from micro-sized corner cubes. The optical resolution and corresponding pixel size of the sensor are key to evaluating feasibility.

For a high-resolution UAV application, we assume that a very large number of sensor pixels partition the ground into an equivalent grid of 5 cm × 5 cm cells. Further assume that the search takes place from an altitude of 1 km. The resolution of the sensor must be

$$\theta_s = 5 \times 10^{-2}\,\text{m}/10^{3}\,\text{m} = 5 \times 10^{-5}\ \text{radian} = 0.05\ \text{mrad}$$

(A more extensive analysis would include the effects of jitter and pointing accuracy.) We arbitrarily let $\lambda = 0.5\ \mu\text{m}$ (green light), because people intuitively have a feel for optical components that operate in the visible. Practical considerations such as clutter, safety, scattering, and the like would probably point to a different λ for many applications. Evaluating the effect of changing the wavelength would be a simple matter.

The sensor diameter must be:

$$D_s = 2.44 \cdot \lambda/\theta_s$$
$$D_s = 2.44 \cdot 5 \cdot 20^{-7}/(5 \cdot 10^{-5})$$
$$D_s = 2.44 \text{ cm}$$

We arbitrarily require that any sensor element receives ten times as strong a signal from the cell with the corner cube as from a cell that does not contain a corner cube. Therefore, from Eq. (3):

$$D_{c(min)} = \left(D_{1p}{}^2\ \lambda^2 \cdot 10/1.055\right)^{1/4}$$
$$D_{c(min)} = [(5 \cdot 10^{-2})^2 \cdot (5 \cdot 10^{-7})^2 \cdot 10/1.055]^{1/4}$$
$$D_{c(min)} = 2.77 \cdot 10^{-4} \text{ m}$$

We require the reflected energy to be intercepted by a sensor located near the illuminator. Assume they are adjacent and of similar aperture size. Diffraction will be used to intentionally spread the beam so that it covers the sensor aperture whether it is above or below, or to the right or to the left, of the illuminator. Therefore, the reflected spot diameter must be equal to two receiver aperture diameters plus one illuminator aperture diameter. If they are all similar, then the spot diameter is three times the sensor diameter. (Even if the illuminator size is negligible, the spot must still cover a disk whose diameter is double that of the sensor.)

We have thus given up a factor of nine in power to ensure geometric coverage of the sensor aperture. We have required an additional factor of ten to ensure sufficient signal-to-clutter ratio. The calculation is made even more conservative by implicitly assuming that the clutter surface has no absorption and has the same reflectance as the cube. Therefore, in the plane of the sensor, the spot reflected by the corner cube is to subtend at least

$$\theta_c = D_{cp}/R$$
$$\theta_c = 3 \cdot 0.0244/1000 = 0.073 \text{ mrad}$$
$$D_{c(max)} = 2.44 \cdot 5 \cdot 10^{-7}/(7.32 \cdot 10^{-5})$$
$$D_{c(max)} = 1.67 \cdot 10^{-2}$$
$$D_{c(max)} = 1.67 \text{ cm}$$

Accordingly, it must have a cube aperture smaller than 1.67 cm.

Accordingly, it must have a cube aperture smaller than 1.67 cm.

Resolution has placed an upper bound on corner cube size. Power constraints determined the lower bound.

Returning to the lower bound relationships, if λ is 25 times larger, at $\lambda = 10 \cdot 10^{-6}$ m, then the corner must be five times wider at

$$D_{c(min)} = 5 \cdot 2.77 \cdot 10^{-4}$$
$$D_{c(min)} = 1.38 \text{ mm, or larger}$$

At this point it is appropriate to mention that the fabrication of such miniature corner cubes requires a great deal of precision and that the shorter wavelengths scatter, rather than follow the computed divergence caused by diffraction. The longer wavelengths, which scatter less, require correspondingly larger diameter apertures throughout the system in order to form images with enough resolution to discriminate one location from its neighbor.

Basic Calculations for an Array of Corner Reflectors

If several of these cubes simultaneously reflect energy back to the same sensor element, the interesting phenomenon of interference patterns starts to take place.

Assuming that all the elemental cubes in an array are identical, the shape of the energy envelope has the broad shape of a single cube. There exists the very unlikely possibility that the phases of all returns from the elemental cubes could exactly reinforce. In that unlikely case, the pattern resembles that of a single large cube with the same diameter as the array diameter. However, in our applications of interest, waves from the elemental cubes interact in an unpredictable manner that is best described statistically.

In general, additional margin is provided via excess laser power to ensure a sufficiently reliable signal at the receiver. A factor is computed for the nominal energy in the central, main spot within the envelope. Then a second factor is applied to account for its variability.

Arrays related to these are used in pseudo-phase conjugation and in experimental studies of atmospheric effects and plate tectonics. An analysis of the performance of such an array would require a separate effort.

Basic Calculations for Laser Power and Receiver Sensitivity

Consider the conventional equations applied to a practical example for the micro application:

$$P_{rcvr} = \frac{P_{trans} \cdot e^{-2\alpha R}}{\pi\left(\theta_{spot} \cdot R^2\right)} \cdot \frac{A_{retro}}{\left(\lambda^2/A_{retro}\right) \cdot R^2} \cdot A_{rcvr}$$

where

P_{rcvr}	=	power on the receiver
P_{trans}	=	power at the transmitter
e^{-a}	=	atmospheric extinction, 0.8/km
R	=	range, 1 km
A_{retro}	=	area of the cube, $4 \bullet 10^{-4}\ m^2$ ($D_{retro} = 2.26$ cm)
A_{rcvr}	=	area of the receiver, $6.25 \bullet 10^{-4}\ m^2$ ($D_{rcvr} = 2.82$ cm)
q_{spot}	=	half angle subtended by the spot 10^{-2} radians
l	=	wavelength, $1.06 \bullet 10^{-6}$ m
P_{rcvr}	=	$P_{trans} \bullet 5.7 \bullet 10^{-8}$

Discard an order of magnitude to more than account for variability due to scintillation and another order due to undefined real-world losses.

$$P_{rcvr} = 5.7 \cdot 10^{-10} \cdot P_{trans}$$

$$\mathrm{SNR} = \frac{P_{rcvr} \cdot \eta}{\mathrm{NEP}}$$

where

SNR	=	Desired signal-to-noise ratio, 100
η	=	quantum efficiency, 0.8
NEP	=	Noise Equivalent Power, $10^{-14} \cdot \sqrt{100\ \text{Hz}}$
	=	10^{-13} W
100	=	$P_{trans} \cdot 4560$
P_{trans}	=	21.9 mW

This is a reasonable power requirement for today's diode lasers.

CONCLUSIONS

In general, the calculations in this appendix confirm that reasonably sized lasers and reasonably sized cubes (or arrays of cubes) can perform in the applications suggested.

Appendix B
MEDS Propellant Requirements

In this appendix, we present a first-order calculation determining the amount of high-energy propellant required to give a MEDS device reasonable mobility.

Assume that we have a silicon MEDS device that is roughly 3 mm square and 50 µm tall (1 = 3 mm, w = 50 µm). This gives the MEDS device a mass of 1.08 mg (m_{MED} = 1.08 mg). We assume that the MEDS moves by "popping" to a given height, assumed here to be 2 m (h = 2 m), and then gliding in the desired direction. If we assume little to no aerodynamic shaping, the drag coefficient may be modeled as that of a rectangular plate ($C_D = 2$). We further assume that the MEDS is capable of orienting itself in launch so as to present a small frontal area in its direction of movement; we assume that the attack angle of the MEDS is sufficiently small that the presented frontal area would be approximately twice the area of one edge of the MEDS ($A_f = 21$ w).

The basic kinematic equation is simply:

$$m_{MED}a = -m_{MED}g - F_d$$

where
- a = acceleration required to reach desired height
- g = acceleration of gravity
- F_d = aerodynamic drag force

Aerodynamic drag is defined as

$$F_d = 1/2\,\rho v^2 A_f C_D$$

where ρ is the density of air. Since we assume $C_D = 2$, the above equation simplifies to

$$F_d = \rho v^2 A_f$$

The differential equation allowing us to calculate the required launch velocity is

$$dt = -\frac{dv}{g + \rho A_f v^2 / m_{MED}}$$

where v is the velocity of the MEDS at any given time t. The solution to this equation is

$$v = v_0 - g/\beta \tan(\beta t)$$

where

$$\beta = \sqrt{\rho g A_f / m_{MED}}$$
$$v_0 = \text{launch velocity}$$

Similarly, one may integrate further to get the jump height, h, of the MEDS device as a function of time:

$$h = v_0 t + g/\beta^2 \ell n \cos(\beta t)$$

We are interested in calculating v_0 for a maximum height, h*. Since the maximum height is reached at the time in which v = 0, the time at which the h* is reached is

$$t = 1/\beta \tan^{-1}(\beta v_0/g)$$

This time may be substituted back into the height equation and simplified to yield,

$$h^* = v_0/\beta \tan^{-1}(\beta v_0/g) + g/\beta^2 \ell n \frac{1}{\sqrt{1 + \left(\beta v_0/g\right)^2}}$$

We may then calculate v_0 for a given h^* through iteration.

The required launch kinetic energy, KE, is

$$KE = 1/2\, m_{MED} v_0^2$$

We assume that the MEDS is launched ultimately via stored chemical energy, and the required chemical energy, CE, is simply

$$CE = \frac{KE}{\varepsilon} = m_{CE} e$$

where ε = energy conversion efficiency
m_{CE} = mass of propellant
e = specific energy of propellant

The required mass of propellant is therefore

$$m_{CE} = \frac{1/2\, m_{MED} v_0^2}{\varepsilon e}$$

Launching our example MEDS device to a 2-m height would require an initial velocity of roughly 6.6 m/sec for a required KE of 23.5 µJ. For fuel, we assume a low-flame-temperature double-base nitrocellulose/diglycol dinitrate propellant with a specific energy of roughly 3 kJ/g. An assumed conversion efficiency of 30 percent then translates into 0.026 µg of propellant required for each jump. Assuming that 1000 jumps would provide sufficient mobility, the final propellant mass required would be 0.026 mg. This would be 2.4 percent of the mass of the MEDS and occupy 3.8 percent of the volume.

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